Contribution from the Department of Chemistry, Kent State University, Kent, Ohio 44242

Phosphato Complexes of Platinum(II): Phosphorus-31 NMR and Kinetics of Formation and Isomerization Studies

Rathindra N. Bose,* Niranjan Goswami,† and Shadi Moghaddas

Received December 27, 1989

Ortho-, pyro-, and triphosphate anions form monodentate phosphato complexes with chloro(diethylenetriamine)platinum(II) chloride and various chelates with dichloro(ethylenediamine)platinum(II) in the pH range 2–11. Monodentate complexations largely proceed through the direct reaction with the $PtCl(dien)^+$ for which bimolecular rate constants were estimated as 2.7×10^{-2}, 1.5×10^{-2}, and 1.2×10^{-2} M^{-1} s^{-1} for the ortho-, pyro-, and triphosphate reactions. Phosphorus-31 NMR spectra reveal coordination chemical shifts of 3–6 ppm for the phosphorus atoms of the bound phosphate groups. Only the monodentate (γ-triphosphato)platinum(II) complex was detected by ^{31}P NMR spectroscopy, although this ligand is capable of coordinating through the β-phosphate group as well. Phosphorus–phosphorus coupling constants for $Pt(dien)(H_2P_2O_7)$ and $Pt(dien)(H_2P_3O_{10})^-$ complexes were found to be in the range 19–23 Hz. Two acidity constants were estimated as 9.8×10^{-5} and 1.5×10^{-10} for $Pt(H_2PO_4)(dien)^+$ and 7.3×10^{-5} and 5.6×10^{-8} for $Pt(H_2P_2O_7)(dien)$ from the pH-dependent ^{31}P chemical shift data. Chelation to dichloro(ethylenediamine)-platinum(II) by pyro- and triphosphate ligands is accomplished primarily through aquations of the platinum substrate. Bimolecular rate constants for the direct reactions with $PtCl_2(en)$ were estimated as 1.9×10^{-3} and 4.6×10^{-4} M^{-1} s^{-1} for the pyro- and triphosphate anions at pH 6.0. The triphosphate ligand forms both β,γ- and α,γ-linkage isomers; the six-membered chelate ring (β,γ-complex) formation dominates at lower pH (3–4), whereas the formation of the eight-membered chelate ring is favored in the pH range >6. Coordinated phosphate groups exhibit 4–12 ppm coordination chemical shifts, and phosphorus–phoshorus coupling constants of 19–22 Hz were observed for the triphosphato chelates. Acidity constants, 6.0×10^{-4} and 8.3×10^{-6}, were calculated for the $Pt(H_2P_2O_7)(en)$ complex. Linkage isomerizations, $\beta,\gamma \rightarrow \alpha,\gamma$ and $\alpha,\gamma \rightarrow \beta,\gamma$, for triphosphato complexes mainly proceed through an intramolecular mechanism for which first order rate constants were estimated as 2×10^{-3} and 3×10^{-3} s^{-1} at pH 3.5 and 7.7.

Introduction

Phosphato complexes of diamagnetic metal ions such as Co(III) and Rh(III) have been used to study the role of metal centers in various enzyme-catalyzed phosphate hydrolysis reactions.[1-9] However, metal ions in biological reactions are mainly divalent rather than trivalent. In this respect, platinum(II) may serve as a better model since the charges on the metal ions appear to influence hydrolyses.[1] Moreover, coordinated water molecules in platinum(II) complexes are much more acidic than those in Co(III); therefore, hydrolysis due to the intramolecular transfer of coordinated hydroxide (hydroxyl transfer reaction) can be followed in acidic solutions. Hence, mechanistic ambiguities associated with the coordinated and uncoordinated hydroxyl transfers as encountered in Co(III) complexes may be removed.[4] One obvious disadvantage of Pt(II) in the hydrolysis of nucleotides is that platinum(II) binds primarily to the nitrogen donor sites of purine and pyrimidine rings and may not promote the hydrolysis. The difficulty can be avoided by examining inorganic phosphate ligands. Moreover, the nitrogen sites in the nucleotide can be blocked by a platinum atom or other metal center that forms substitution-inert complexes, and a second platinum atom can be used to promote hydrolysis. Since phosphate hydrolysis is conveniently followed by phosphorus-31 NMR spectroscopy, various phosphato complexes of platinum(II) need to be characterized. The coordination ability of phosphate groups has not been explored in detail[10-15] although an extensive development of platinum(II) biochemistry has occurred since the discovery of the antineoplastic activity of *cis*-diamminedichloroplatinum(II).[16,17] Here we report phosphorus-31 NMR characterization of various monodentate and bidentate phosphato complexes of Pt(II) utilizing a variety of platinum substrates and inorganic phosphate ligands. In an earlier study,[14a] we documented the rates of formation of pyro- and triphosphato chelates of diamminedichloroplatinum(II) and noted that the α,γ-triphosphato chelate was the major product for the triphosphate reaction. The present study includes the kinetics of formation of various monodentate phosphato complexes and their phosphorus-31 NMR characterization. We present here evidence of rapid intramolecular linkage isomerization of triphosphate chelates which leads to the formation of an eight-membered chelate ring (α,γ complex) rather than the more usual six membered β,γ complex. An intramolecular linkage isomerization

* To whom communication should be addressed.
† Current address: Department of Chemistry, University of Missouri, Columbia, MO.

(1) See, for example: Cleland, W. W. *Methods Enzymol.* **1982**, *87*, 159. Cooperman, B. S. *Met. Ions Biol. Syst.* **1976**, *5*, 79. Mildvan, A. S. *Adv. Enzymol. Relat. Areas Mol. Biol.* **1979**, *49*, 103–125. Sigel, H. *Pure Appl. Chem.* **1983**, *55*, 137.
(2) Hosseini, M. W.; Lehn, J. M.; Maggiora, L.; Mertes, K. B.; Mertes, M. P. *J. Am. Chem. Soc.* **1987**, *109*, 537. Yohannes, P. G.; Plute, K. E.; Mertes, M. P.; Mertes, K. B. *Inorg. Chem.* **1987**, *26*, 1751. Yannes, P. G.; Mertes, M. P.; Mertes, K. B. *J. Am. Chem. Soc.* **1985**, *107*, 8288.
(3) Milburn, R. M.; Basak, G. M.; Tribolet, R.; Sigel, H. *J. Am. Chem. Soc.* **1985**, *16*, 165. Hubner, P. W. A.; Milburn, R. M. *Inorg. Chem.* **1980**, *19*, 1267.
(4) Jones, D. R.; Lindoy, L. F.; Sargeson, A. M. *J. Am. Chem. Soc.* **1984**, *106*, 7807; **1983**, *105*, 7327. Anderson, B.; Milburn, R. M.; Harrowfield, J. M.; Robertson, G. B.; Sargeson, A. M. *J. Am. Chem. Soc.* **1987**, *99*, 2652. Jones, D. R.; Lindoy, F. L.; Sargeson, A. M.; Snow, M. R. *Inorg. Chem.* **1982**, *21*, 4155.
(5) (a) Cornelius, R. D. *Inorg. Chem.* **1980**, *19*, 1285. Norman, P. R.; Cornelius, R. D. *J. Am. Chem. Soc.* **1982**, *104*, 2356. (b) Harmony, T. P.; Gilletti, P. F.; Cornelius, R. D.; Sundaralingam, M. *J. Am. Chem. Soc.* **1984**, *106*, 2812.
(6) Wolterman, G. M.; Belford, R. L.; Haight, G. P. *Inorg. Chem.* **1977**, *16*, 2985. Imamura, T.; Hinton, D. M.; Belford, R. L.; Gumport, R. I.; Haight, G. P. *J. Inorg. Biochem.* **1979**, *11*, 241.
(7) (a) Bose, R. N.; Viola, R. D.; Cornelius, R. D. *Inorg. Chem.* **1984**, *23*, 1181. (b) *Inorg. Chem.* **1985**, *24*, 3989.
(8) Zichun, L.; Shorter, A. L.; Lin, I.; Dunaway-Mariano, D. *Inorg. Chem.* **1988**, *27*, 4135. Lin, I.; Knight, W. B.; Ting, S.-J.; Dunaway-Mariano, D. *Inorg. Chem.* **1984**, *23*, 988.
(9) Speckhard, D. C.; Pecoraro, V. L.; Knight, W. B.; Cleland, W. W. *J. Am. Chem. Soc.* **1986**, *108*, 4167. For corrections, see: *J. Am. Chem. Soc.* **1988**, *110*, 2349.
(10) Stanko, J. A. *Platinum Coordination Complexes in Cancer Chemotherapy*; Conners, T. A., Robert, J. J., Eds.; Springer-Verlag: New York, 1974; p 25.
(11) Louie, S.; Bau, R. *J. Am. Chem. Soc.* **1977**, *99*, 3874. Bau, R.; Sharon, K. S.; Huang, J.-A. F.; McKenna, C. E. *J. Am. Chem. Soc.* **1988**, *110*, 7546.
(12) Appleton, T. G.; Hall, J. R.; McMahan, I. J. *Inorg. Chem.* **1986**, *25*, 726. Appleton, T. G.; Berry, R. D.; Hall, J. R. *Inorg. Chim. Acta* **1982**, *64*, 1229.
(13) Wood, F. E.; Hunt, C. T.; Balch, A. L. *Inorg. Chim. Acta* **1982**, *67*, 119.
(14) (a) Bose, R. N.; Viola, R. E.; Cornelius, R. D. *J. Am. Chem. Soc.* **1984**, *106*, 3336. (b) *Ibid.* **1986**, *108*, 4403.
(15) Reily, M. D.; Marzilli, L. G. *J. Am. Chem. Soc.* **1986**, *108*, 8299. Reily, M. D.; Hambley, T. W.; Marzilli, L. G. *J. Am. Chem. Soc.* **1988**, *110*, 2999.
(16) The antitumor activity of *cis*-diamminedichloroplatinum(II) was first reported in 1969: Rosenberg, B.; Van Camp, L.; Trosko, J. E.; Mansour, V. H.; *Nature (London)* **1969**, *222*, 388.
(17) The current status of the drug has been reported: Sherman, S. E.; Lippard, S. L. *Chem. Rev.* **1987**, *87*, 1153.

0020-1669/90/1329-3461$02.50/0

in platinum complexes has been reported recently by Reedijk's group,[18a] who describe N1 and N7 coordination of 9-ethylguanosine in the Pt(dien)(9-ethylguanine) complex. A linkage isomerization due to the migration of N7 to N1 binding by inosine to Pt(II) might also occur as reported by Martin,[18b] for which this author suggested a binuclear N1–N7 bound intermediate.

Experimental Section

Materials. The platinum substrates, dichloro(ethylenediamine)platinum(II) ($PtCl_2$(en)) and chloro(diethylenetriamine)platinum(II) chloride ([PtCl(dien)]Cl), were synthesized by the established methods.[19,20] Sodium salts of ortho-, pyro-, and triphosphates (Aldrich) were used without further purification. Sodium hydroxide and perchloric acid were standardized before use. Anhydrous sodium perchlorate (Aldrich) was also used without further purification.

Physical Measurements. Magnetic resonance studies were performed on a GE 300-MHz (GN 300) instrument equipped with a broad-band probe. All spectra were recorded in D_2O (99.8% atom) in either 5-mm or 10-mm sample tubes. Chemical shifts are with respect to 85% phosphoric acid as an external reference. Typical data acquisition parameters are as follows: 126.5-MHz spectropholmeter frequency; 90° pule of 25-s duration; 2-s pulse delay time; 8000-Hz spectral width; 8K to 32K data points. A relatively smaller frequency window, 4000 Hz with 32K data points, was selected for experiments where integrations of signals were sought. The total delay time between pulses (acquisition time plus pulse delay time) was about 4.5 s, which is sufficient to ensure >95% relaxation[21] before the onset of the next pulse. Since the concentration of $PtCl_2$(en) was 5×10^{-4} M, at least 2000 accumulations were necessary to record a spectrum with signal to noise ratio greater than 20. For the $[PtCl(dien)]^+$ reactions, 256 acquisitions were sufficient.

Rate Measurements. The reactions of various platinum substrates with the phosphate ligands were carried out under pseudo-first-order conditions by using excess phosphate. Reaction mixtures were self-buffered by the phosphates. Reactions of $PtCl_2$(en) and $PtCl(dien)^+$ were followed at 260 and 280 nm. Pseudo-first-order rate constants were evaluated either from semilogarithmic first-order plots (ln $D - D_\infty$ vs t) or by use of an iterative least-squares computer program according to eq 1 where

$$D = (D_0 - D_\infty)e^{-k_0t} + D_\infty \qquad (1)$$

D_0, D, and D_∞ are the absorbances at time $t = 0$, at time t, and at infinite time and k_0 represents the first-order rate constant. The first order plots were usually linear for more than 4 half-lives.

Rates of isomerization of (triphosphato)platinum(II) chelates were estimated from the time domain ^{31}P NMR signals.[22] These experiments were performed by using a data acquisition subroutine "Kinet", with which our GE NMR instrument was equipped. This subroutine allows us to collect and save FIDs according to preprogrammed acquisition parameters at desired time intervals. For a particular kinetic run, the data acquisition parameters (including the number of transient for each spectrum) were kept invariant. These parameters were identical with those listed earlier except that only 16 transients were accumulated. Spectra were then generated from these FIDs, and the integrated peak intensities of the desired signal were retrieved from the spectra. The integrated signal intensities of the β,γ chelate (combined intensities of β- and γ-phosphorus atoms only) and the α,γ chelate (combined intensities of α- and γ-phosphorus atoms only) at the specified time intervals were then calculated. Rate constants were then estimated from half-lives. For example, when (β,γ-triphosphato)platinum(II)–(α,γ-triphosphato)platinum(II) isomerization was followed by raising the pH by 3.0 to pH 7.7, the ^{31}P resonances for the latter isomer increased in intensity but eventually leveled off. The peak intensities for the β,γ-isomer concomitantly decreased with time and attained a limiting value at infinite time. The half-lives of the isomerization process were then calculated by noting the time required to attain half of the intensity difference (ΔI) at a given time ($\Delta I = I_t - I_\infty$ or $I_\infty - I_t$; I_t is the intensity at any time, and I_∞ is the limiting intensity at infinite time). Since the isomerization reactions were relatively fast ($t_{1/2} \approx$ 3–5 min), a more convenient method based on UV–vis spectroscopy was tried. The spectral features for the two isomers were not sufficiently different to allow us to monitor the conversion of one isomer to the other.

Evaluation of Acidity Constants. Acidity constants of some phosphatoplatinum(II) complexes were calculated from phosphorus-31 chemical shift-pH profiles. Since these experiments were performed in D_2O, the pH-meter reading (pD) was corrected[23] by utilizing the relationship pH = pD + 0.4. These corrected values were used to evaluate the acidity constants. These chemical shifts depend on the state of protonation of the phosphate ligands. Most of the complexes examined act as diprotic acids in the pH range 2–10. Two acidity constants correspond to eqs 2 and 3, where An is either diethylenetriamine or ethylenediamine and P_x represents the phosphate anions. At any given pH, the measured chemical shift, δ, is expressed as shown in (4). In these expressions, f_1, f_2, and f_3 represent the fractions of $AnPtH_2P_x^{n+}$, $AnPtHP_x^{(n-1)+}$, and $AnPtP_x^{(n-2)+}$ ($f_1 + f_2 + f_3 = 1.0$) present in solution and δ_1 through δ_3 are chemical shifts of these three forms. The values of K_{a_1} and K_{a_2} and the chemical shift parameters were evaluated from the fit of eq 5 by the

$$AnPtH_2P_x^{n+} + H_2O \underset{}{\overset{K_{a_1}}{\rightleftharpoons}} AnPtHP_x^{(n-1)+} + H_3O^+ \qquad (2)$$

$$AnPtHP_x^{(n-1)+} + H_2O \underset{}{\overset{K_{a_2}}{\rightleftharpoons}} AnPtP_x^{(n-2)+} + H_3O^+ \qquad (3)$$

$$\delta = \delta_1 f_1 + \delta_2 f_2 + \delta_3 f_3 \qquad (4)$$

$$\delta = \frac{\delta_1[H_3O^+]^2 + \delta_2 K_{a_1}[H_3O^+] + \delta_3 K_{a_1}K_{a_2}}{[H_3O^+]^2 + K_{a_1}[H_3O^+] + K_{a_1}K_{a_2}} \qquad (5)$$

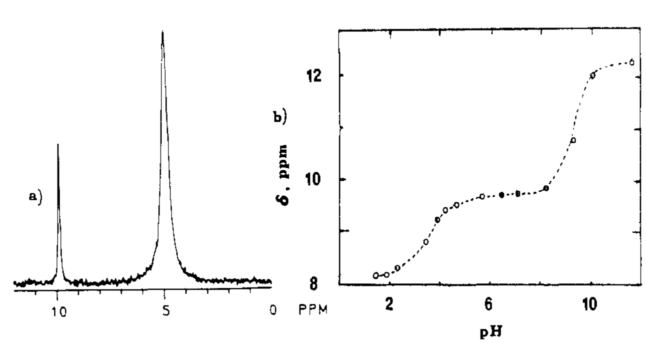


Figure 1. (a) 126.5-MHz phosphorus-31 NMR spectrum of $PtCl(dien)^+$ (2.0 mM) plus orthophosphate anion (20 mM) reaction mixture at pH 8.25. The peak at 9.84 is for the orthophosphato complex (I), and the signal at 4.88 ppm is for the free ligand. (b) Plot of chemical shift-pH data (Table I) for the orthophosphato complex.

Table I. Phosphorus-31 Chemical Shifts as a Function of pH for Free Orthophosphate Anion and $Pt(H_2PO_4)(dien)^+$ Cation with Values in Parentheses Calculated by Using Equation 5[a,b]

	chem shift, ppm		
pD[c]	free PO_4 anion	Pt–PO_4 complex	coord chem shift,[d] ppm
1.55	2.40	8.22 (8.23)	5.82
1.89	2.41	8.23 (8.24)	5.82
2.39	2.44	8.31 (8.30)	5.87
3.45	2.46	8.85 (8.83)	6.39
3.99	2.45	9.26 (9.27)	6.81
4.34	2.45	9.44 (9.49)	6.99
4.65	2.47	9.58 (9.58)	7.11
5.70	2.66	9.73 (9.69)	7.17
6.55	3.22	9.74 (9.71)	6.42
7.07	3.82	9.77 (9.72)	5.95
8.25	4.88	9.84 (9.86)	4.96
9.34	5.13	10.69 (10.9)	5.56
10.1	5.56	12.09 (11.9)	6.53
11.89	5.87	12.24 (12.31)	6.37

[a] Calculated values are based on $K_{a_1} = 9.8 \times 10^{-5}$, $K_{a_2} = 1.5 \times 10^{-10}$, $\delta_1 = 8.21$, $\delta_2 = 9.70$, and $\delta_3 = 12.31$. [b] pH-meter reading was corrected for this calculation. [c] Uncorrected pH meter reading. [d] Positive values inicate downfield shift in comparison to values for the free phosphate anion.

(18) (a) Van der Veer, J. L.; Van den Eist, H.; Reedijk, J. *Inorg. Chem.* **1987**, *26*, 1936. (b) Martin, R. B. *ACS Symp. Ser.* **1983**, *No. 209*, 231.
(19) Heneghan, L. F.; Bailar, J. C. *J. Am. Chem. Soc.* **1953**, *75*, 1840.
(20) Watt, G. W.; Cude, W. A. *Inorg. Chem.* **1968**, *7*, 335.
(21) Spin-lattice relaxation times for various phosphato chelates lie in the range 0.5–0.8 s, as determined by inversion recovery method. For example, the T_1 for α- and γ-phosphorus atoms in the α,γ-triphosphato chelate was evaluated as 0.49 ± 0.02 s. Relaxation studies for ^{31}P nuclei of Pt(II)–phosphato and –nucleotide complexes are in progress and will be published elsewhere.
(22) In these experiments, preaquated *cis*-$PtCl_2$(en) was used, allowing us a much higher concentration (5×10^{-3} M) of the platinum substrates. The ^{31}P spectra can be recorded from 16 transients.
(23) Glasoe, P. K.; Long, F. A. *J. Phys. Chem.* **1960**, *64*, 188.

use of an iterative nonlinear least-squares computer program.[24] The acidity constants and chemical shifts are reported in appropriate tables.

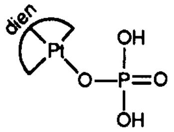
Results and Discussion

I. Phosphorus-31 NMR Characterization of Products. A. Orthophosphato Complexes of Platinum(II). Figure 1 shows the phosphorus-31 NMR spectrum of the orthophosphato complex formed by the reactions of the phosphate ligand with $PtCl(dien)^+$. The intense upfield signal is due to the free phosphate, and the downfield signal is for the phosphate group coordinated to platinum.[25] The chemical shifts for the phosphorus-31 resonances at various pH values, along with coordination chemical shifts, are listed in Table I. Coordination chemical shifts about 5–7 ppm can be noted for the orthophosphato complex over the pH range 1.5–12.

The inset in Figure 1 displays the pH–δ profile of $Pt(H_2PO_4)(dien)$ (I), which exhibits two inflections. The pK_{a_1} and pK_{a_2} values corresponding to the successive depronotonations (6) and (7) were calculated to be and 4.0 and 9.8.

$$Pt(dien)PO_4H_2^+ + H_2O \rightleftharpoons Pt(dien)(PO_4H) + H_3O^+ \quad (6)$$

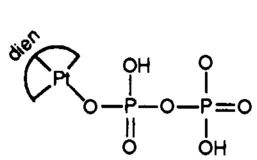
$$Pt(dien)(PO_4H) + H_2O \rightleftharpoons Pt(dien)(PO_4)^- + H_3O^+ \quad (7)$$



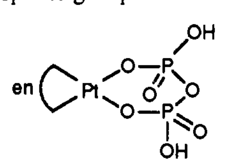
I

The reaction of orthophosphate anion with $PtCl_2(en)$ resulted in the formation of a green complex. We did not characterize this complex since Appleton and workers[12] have characterized various phosphato blue and green complexes of *cis*-$PtCl_2(NH_3)_2$ and $PtCl_2(en)$ by using ^{31}P, ^{195}Pt, ^{15}N NMR spectroscopy. These complexes are reported to be monodentate monomer and bridging phosphato complexes consisting of dimer and higher oligomers including mixed-valence platinum(II,III) compounds.

B. Pyrophosphato Complexes of Platinum(II). Figure 2 presents the phosphorus-31 NMR spectra of pyrophosphato complexes of $PtCl(dien)^+$ and $PtCl_2(en)_2$. The first platinum compound forms the monodentate pyrophosphato complex, $Pt(P_2O_7H_2)(dien)$ (II). The two phosphate groups in this mono-



II



III

dentate phosphato complexes are magnetically nonequivalent. Two doublets for the coordinated pyrophosphate anion and a singlet for the free ligand are expected in the ^{31}P spectra of the reaction mixtures containing excess ligand. The downfield doublet in Figure 2a is for the coordinated phosphate group (β-phosphate), while the upfield doublets are for the uncoordinated α-phosphate group. The doublet arising from the uncomplexed phosphate end is clearly observed at some pH values, but at other pHs this signal is partly or completely masked under the broad peak of the free pyrophosphate.

The reaction of this phosphate ligand with the $PtCl_2(en)$ yielded a chelate, as is evident from the ^{31}P spectrum (Figure 2b). The

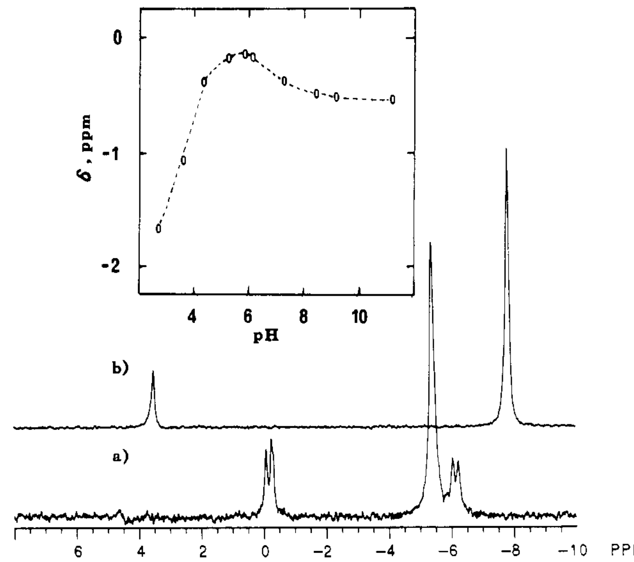


Figure 2. 126.5-MHz phosphorus-31 NMR spectra of the pyrophosphato complexes of $PtCl(dien)^+$ and *cis*-$PtCl^2(en)$ in the presence of excess pyrophosphate anion. Part a: $PtCl(dien)^+$ (2.0 mM) and pyrophosphate anion (15 mM) at pH 6.90 after 6 h of mixing. Two doublets centered at −0.25 and −6.21 ppm arise from the monodentate pyrophosphato complex (II), and the intense peak at −5.35 ppm is for the free pyrophosphate anion. Part b: $PtCl_2(en)$ (0.5 mM) and pyrophosphate anion (4.0 mM) after 24 h of mixing at pH 5.12. The peaks at 3.49 and −7.87 ppm are for the pyrophosphate chelate and free ligand. The inset exhibits the pH–δ profile for the pyrophosphato complex (II).

Table II. Phosphorus-31 Chemical Shifts as a Function of pH for $Pt(H_2P_2O_7)(dien)$ Complex with Values in Parentheses Being the Phosphorus–Phosphorus Coupling Constants in Hz

	chem shift, ppm		
pD[a]	obsd[b]	calcd[c,d]	coord chem shift,[e] ppm
2.70	−1.66 (19)	−1.67	6.43
	−10.65 (19)		−2.56
3.65	−1.05 (19)	−1.03	6.91
	−8.15 (19)		−0.19
4.38	−0.36[f] (20)	−0.39	7.55
5.23	−0.17 (22)	−0.14	7.38
	−7.78[g]		−0.22
5.83	−0.11 (21)	−0.12	6.59
	−7.35 (21)		−0.65
6.09	−0.15 (22)	−0.14	6.36
	−7.25 (21)		−0.74
7.20	−0.37 (20)	−0.37	4.96
	−5.52 (20)		−0.46
8.52	−0.44 (22)	−0.48	4.04
	−4.26[a]		−0.22
9.15	−0.52 (22)	−0.49	3.50
	−4.20[g]		−0.18
11.15	−0.53 (23)	−0.50	3.15
	−4.18		−0.50

[a] Uncorrected pH meter reading. [b] Peaks appear as doublets and the reported shifts are the center of the doublets. [c] Calculated values are based on $K_{a_1} = 7.3 \times 10^{-5}$, $K_{a_2} = 5.6 \times 10^{-8}$, $\delta_1 = -1.81$, $\delta_2 = -0.072$, and $\delta_3 = -0.50$. [d] Corrected hydrogen ion concentrations were used in this calculation. [e] Positive and negative values indicate downfield and upfield with repect to the values for uncoordinated ligand. [f] The doublet for the three phosphate end of coordinated pyrophosphate was completely masked under free pyrophosphate peak. The doublet was partly masked under free pyrophosphate peak.

(24) Easom, K. A.; Bose, R. N. *Inorg. Chem.* **1988**, *27*, 2331.

(25) One reviewer's comment regarding the absence of $^{31}P-^{195}Pt$ couplings in the ^{31}P spectra deserves response. This two-bond coupling (8 Hz) was observed (as a satellite) in $Pt(P_2O_7)(NH_3)_2^{2-}$ on a 90-MHz instrument. However, we do not see the coupling for the complex using a 300- or 500-MHz instrument. This coupling was not observed for other phosphato[7,11,12,15] and phosphonato complexes (even at low field, 90 MHz) including those where X-ray crystal structures have been established.[26] The absence of the coupling may be due to a smaller two-bond coupling constant, use of higher magnetic fields, and chemical anisotropic relaxations as have been cited as possible reasons for not observing coupling in other instances.[27] We are reluctant, however, to commit specific reasons for the absence of coupling in the spectra.

(26) Crystal structures of these phosphato and phosphonato complexes[11] were established by Bau's research group, and we have investigated the detailed kinetic of formation and ^{31}P spectra for these complexes (manuscript in preparation). Phosphorus-31 spectra of these complexes do not exhibit $^{31}P-^{195}Pt$ couplings.

(27) See, for example: Lallemand, J. Y.; Solulie, J.; Chottard, J. C. *J. Chem. Soc., Chem. Commun.* **1980**, 436–437. Chottard, J. C.; Girault, J. P.; Chottard, G.; Lallemand, J. Y.; Mansey, D. J. *J. Am. Chem. Soc.* **1980**, *102*, 5565–5572.

Table III. Phosphorus-31 Chemical Shifts as a Function of pH for $Pt(H_2P_2O_7)(en)$

pD[a]	chem shift, ppm	coord chem shift,[c] ppm
2.02	2.29 (2.29)[b]	10.7
3.20	3.10 (3.11)	11.3
4.01	3.52 (3.47)	11.7
4.43	3.53 (3.54)	11.7
5.24	3.59 (3.61)	11.4
5.90	3.61 (3.64)	10.3
6.61	3.69 (3.65)	9.19
7.18	3.65 (3.65)	9.18
8.12	3.65 (3.65)	8.59
9.46	3.64 (3.65)	8.51

[a] Uncorrected pH meter reading. [b] Calculated values based on $K_{a_1} = 6.0 \times 10^{-4}$, $K_{a_2} = 8.3 \times 10^{-6}$, $\delta_1 = 2.09$, $\delta_2 = 3.52$, and $\delta_3 = 3.65$. [c] Positive values indicate downfield shift with respect to those for the free ligand.

phoshpate groups in the chelating pyrophosphate chelate (III) are equivalent (as in the free phosphate ligand), and only singlet resonances are expected in the spectrum. The peak at 3.53 ppm, about 12 ppm downfield from the free pyrophosphate peak, is for the pyrophosphate chelate. This chelate maintains a 9–12 ppm coordination chemical shift in its ^{31}P resonances in the pH range 2–9, although both the complexed and uncomplexed phosphate ligands exhibit changes in chemical shift as a function of pH.

Tables II and III list chemical shifts and coordination chemical shifts of monodentate and bidentate pyrophosphato complexes as a function of pH. The coupling constants $^2J_{P-O-P}$ for the monodentate phosphato complexes lie in the range 19–23 Hz. The pH–δ profile for the coordinated phosphate group of $[Pt(H_2P_2O_7)(dien)]$ is shown in Figure 2.

For the monodentate pyrophosphato complex, three acidity constants corresponding to the dissociation of two protons from the uncoordinated group and one from the coordinated phosphate groups, are expected. The pH–δ profile of the coordinated phosphate group exhibits an initial downfield shift, followed by a small upfield shift in δ with the increase in pH. The initial larger change is most probably associated with deprotonation of the coordinated phosphate group, and the secondary small changes are due perhaps to ionization from uncoordinated phosphate groups (since the latter dissociation is expected to affect the chemical shift of the coordinated phosphate group only insignificantly). Therefore, pK_a values of 4.1 and 7.3 are assigned to protons attached to the coordinated and uncoordinated phosphate groups. When δ values for the uncoordinated phosphate group, as a function of pH, were fitted to a diprotic titration curve, two pK_a values, 2.8 and 7.3, were evolved. The latter value shows up in both the profiles. The lower pK_a, 2.8, is perhaps the first ionization of a proton of the uncoordinated phosphate that exerted negligible influence on the chemical shift of the coordinated phosphorus atom.

Chemical shifts for phosphate ligands and phosphato complexes of diamagnetic metal ions generally increase continuously with increasing pH but eventually level off due to complete deprotonation of phosphate groups. The observed dichotomous behavior in the pH–δ profile may indicate hydrogen bond formation between the uncoordinated phosphate end and the hydrogen atoms of the amine nitrogen in coordinated dien molecules. Such hydrogen bond formation between amine hydrogen and phosphate oxygen in platinum(II) nucleotide complexes has been documented by Lippard's group[28] and Marzilli's group.[29] The extent of hydrogen-bond formation should then depend on the degree of deprotonation of the phosphate group. For the pyrophosphato chelate, on the other hand, both phosphate groups are coordinated to platinum, and the stereochemical requirements do not favor such a hydrogen bond. Two pK_a values estimated from the pH-dependent chemical shift data for the $Pt(H_2P_2O_7)(en)$ are 6.0×10^{-4} and 8.3×10^{-6}.

(28) Caradonna, J. P.; Lippard, S. J. *Inorg. Chem.* **1988**, *27*, 1454.
(29) Reily, M. D.; Marzilli, L. G. *J. Am. Chem. Soc.* **1985**, *107*, 4916.

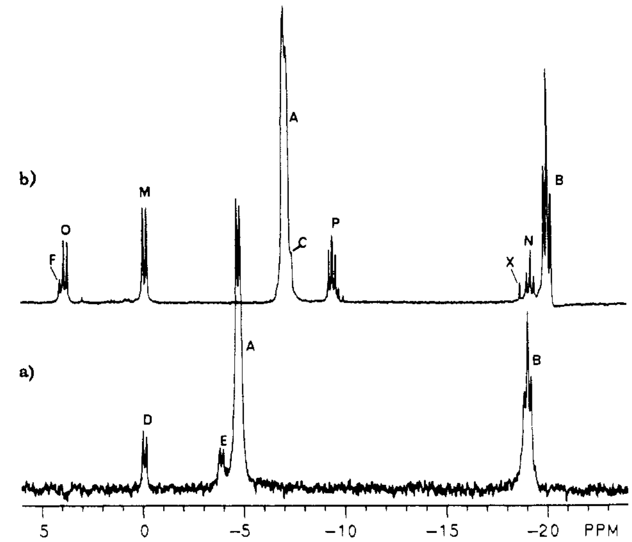


Figure 3. 126.5-MHz phosphorus-31 NMR spectra of triphosphato complexes of platinum(II) in the presence of excess ligand. Signals A and B are for the free triphosphate anion, C and X are for pyrophosphate and an unknown impurity, and F is for the pyrophosphato chelate. Part a: $PtCl(dien)^+$ (1.2 mM) and triphosphate anion (20 mM) at pH 7.90 after 6 h of mixing. Doublets D and E are for the γ- and α-phosphorus atoms of the monodentate complex (VI). The triplet for β-phosphorus is masked under B and is seen separately at pH >8.5. Part B: $PtCl_2(en)$ (0.5 mM), triphosphate anion (5.0 mM) at pH 5.90. Peaks M and N are for the α,γ chelate, and peaks O and P are for the β,γ-chelate.

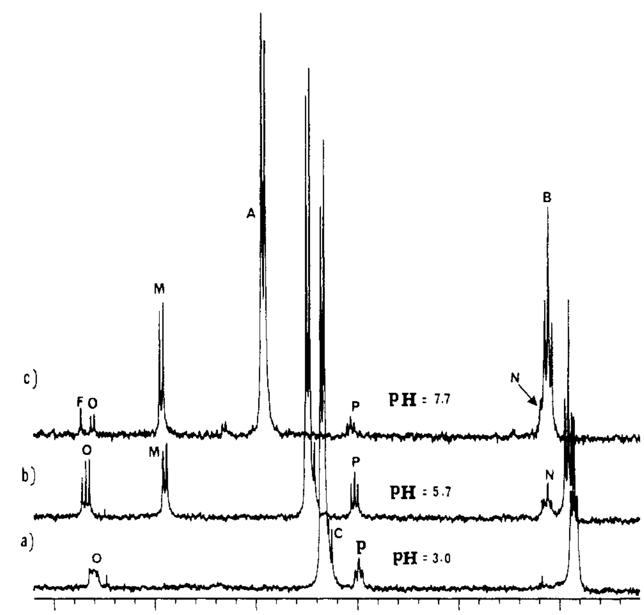


Figure 4. 126.5-MHz phosphorus-31 NMR spectra of triphosphato chelates indicating pH-dependent distribution of α,γ- and β,γ-linkage isomers. Peak labelings are the same as those in Figure 3.

C. Triphosphato Complexes of Platinum(II). Triphosphate anion upon reaction with $PtCl(dien)^+$ forms a monodentate complex and bidentate chelates[30] with $PtCl_2(en)$. Figure 3 exhibits

(30) Phosphorus-31 NMR spectra of the platinum(II) complexes were interpreted on the basis of coordination chemical shifts, P–P couplings, and the peak intensities. These spectra closely resemble to that of Co(III) complexes where X-ray crystal structures have been established.[5b,31] For example, in the β,γ-triphosphato chelate, the ^{31}P chemical shift for β- and γ-phosphorous atoms show a 6–10 ppm downfield shift upon complexation as compared to the shift uncomplexed ligand, and the α-phosphorus atom does not exhibit any significant change in chemical shift. Moreover, in this complex, all three phosphorus atoms are magnetically nonequivalent and the spectrum should appear as two doublets for the α- and γ-phosphorus atoms and doublets of doublets for the β-phosphorus atoms, which is observed in the spectrum.

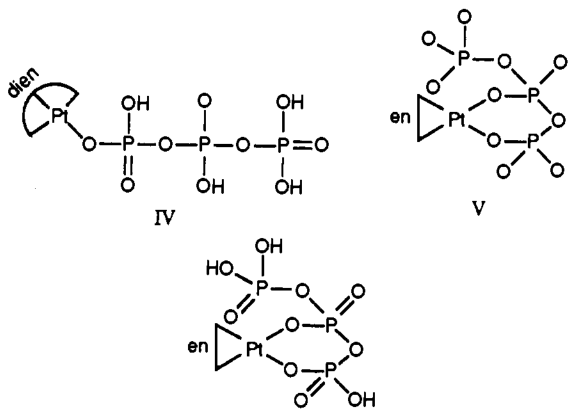
Table IV. Phosphorus-31 Chemical Shifts as a Function of pH for $Pt(H_2P_3O_{10})(dien)^-$ with Values in Parentheses Being the Phosphorus-Phosphorus Coupling Constants in Hz

	chem shift, ppm		
pD[a]	γ-phosphate	β-phosphate	α-phosphate
2.70	−2.40[b] (19)	*d*	*d*
4.33	−0.61 (19)	*d*	*d*
5.49	−0.30[b] (22)	*d*	7.68[b] (21)
6.3	−0.23[b] (22)	*d*	6.90[b] (22)
7.9	−0.11 (21)	*d*	3.91[b] (21)
9.16	−0.07[b] (21)	−19.13[c]	*c*

[a] Uncorrected pH meter reading. [b] Doublet. [c] Triplet. [d] Partly or fully marked under the peaks for the free triphosphate anion.

the phosphorus-31 NMR spectra of our triphosphato complexes.

The doublet A and the triplet B are for the free triphosphate, and the signal C is due to the presence of pyrophosphate impurity. Two new doublets, D and E, are observed for the product in the pH range 2–8. In addition to the doublet D, a new triplet was also observed at pH > 8.5. These signals, along with chemical shifts, are consistent with the formation of triphosphato complex in which the γ-phosphate group is bound to the Pt, $[Pt(\gamma\text{-}P_3O_{10})(dien)]$ (IV). The coordinated terminal phosphate group

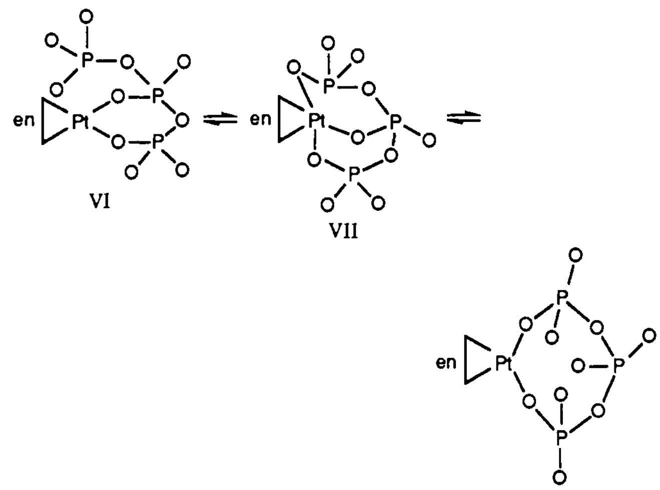


IV V VI

shows a 4–7 ppm downfield shift with respect to free triphosphate, whereas the unbound β- and α-phosphate groups show small coordination chemical shifts. The peaks for the latter two phosphorus atoms were partly or fully masked under the peaks for free triphosphate at some pH's (Table IV). Two pK_a values near 4 and 7 can be estimated from the limited data available on the coordinated γ-phosphate group.

The formation of triphosphato chelates is evident from the ^{31}P spectrum (Figure 3b). From the intensities of the signals and coupling constants, two distinct sets of resonances can be evaluated. First the doublet M and the triplet N show an intensity ratio, 2:1, with a coupling contant of 22 Hz. The doublet (O) and doublets of doublet (P) bear an intensity ratio of 1:1. Coupling constants for those resonances can be calculated as 22 Hz for the doublet and 22 and 21 Hz for the doublets of doublet. These two sets of signals can be rationalized on the basis of formation of two linkage isomers, β,γ and α,γ chelates, as has been observed for Co(III) complexes[5] and *cis*-diamminedichloroplatinum(II).[14a] The peaks M and N arise from the α,γ isomer, an eight-membered chelate ring (V); resonances O and P correspond to the β,γ isomer (VI). The missing resonances (doublet) for the uncoordinated α-phosphate group in the latter isomer are perhaps masked under the doublet of the free triphosphate. The triplet N was clearly observed at some pH values, but at other pH values, it was partly or fully masked. The distribution of the two isomers depends on pH. Table V lists the pertinent NMR data and the distribution

Scheme I



VI VII V

of these isomers as a function of pH.

The chemical shifts associated with coordinated β- and γ-phosphorus groups in the β,γ chelate exhibit small changes with pH. Although the pH–δ profile is not steep enough to allow precise estimation of the acidity constants, pK_a values near 3 and 7 are consistent with the data. Likewise, a pK_a value around 6.5 can be discerned for the α,γ complex.

In an earlier paper,[14a] we have documented that the α,γ chelate was the dominant product (~90%) at pH 8.0 for the reaction of $PtCl_2(NH_3)_2$ with triphosphate anion. On the other hand, the β,γ complex is the dominant product for the Co(III) complexes.[5] Although there is a size difference between these two metal centers, we have performed NMR experiments in the pH range 3–9 in order to determine the influence of pH on the distribution of the two linkage isomers. When the pH was raised from 5.4 to 8.4, the α,γ isomer was the major product (>90%), and the peaks O and P almost disappeared. The isomers were redistributed to a ratio 3([β,γ]/[α,γ]) when the pH was lowered to 4.4. This redistribution in products is due to an intramolecular linkage isomerization (see next section).

II. Kinetics and Mechanisms of Formation of Platinum(II) Phosphato Complexes. The pseudo-first-order rate constants for phosphate complexation to the two platinum(II) substrates, $PtCl(dien)^+$ and $PtCl_2(en)$ follow a straightforward binomial rate law

$$k_0 = k_1 + k_2[P_x] \tag{8}$$

where k_0 is the observed pseudo first order rate constants and P_x represents ortho-, pyro-, or triphosphate ligands. Variations of the first-order rate constants as functions of phosphate concentrations are listed in Table VI. The values of k_1 and k_2, as obtained from the linear least-squares fits of eq 8, also appear in Table VI. The value of k_1 for the *cis*-dichloro complex is found to be the same $[(1.1 \pm 0.1) \times 10^{-4}\ s^{-1}$ at 40 °C] irrespective of the choice of phosphate ligands. The rate constant for this aquation, $5.0\ \tau\ 10^{-5}\ s^{-1}$, is reported by Basolo and co-workers[32] at 35 °C; a 2-fold increase in rate constant with an increase of 5 °C should be noted. The first-order rate constant for the aquation of $PtCl(dien)^+$ was found to be $(6.3 \pm 0.6) \times 10^{-4}\ s^{-1}$ at 40 °C, which can be compared with 2.0×10^{-4} at 30 °C reported by Gray et al.[33]

Rate laws for the formation of phosphato complexes are consistent with the established substitution mechanism of platinum(II) in which the original platinum substrate undergoes parallel aquation and direct reaction with ligands. Further, the aquated species reacts rapidly with the ligands, and this step is not rate

(31) Merritt, E. A.; Sundaralingam, M.; Cornelius, R. D. *J. Am. Chem. Soc.* **1980**, *102*, 6151–6153. Merritt, E. A.; Sundaralingam, M.; Cornelius, R. D.; Cleland, W. W. *Biochemistry* **1978**, *17*, 3274–3278.

(32) Belluco, U.; Cattalini, L.; Basolo, F.; Pearson, R. G.; Turco, A. *J. Am. Chem. Soc.* **1965**, *87*, 241.

(33) Gray, H. B.; Olcott, R. J. *Inorg. Chem.* **1962**, *1*, 481.

Table V. Dependence of Phosphorus-31 Chemical Shifts for Triphosphate Anion, (Ethylenediamine)(α,γ-, and (Ethylenediamine)(β,γ-triphosphato)platinum(II) Chelates with Phosphorus-Phosphorus Coupling Constants Presented in Parentheses

	chem shift, ppm			coord chem shifts, ppm		
pD	free P3010 anion[a]	β,γ chelate	α,γ chelate	β,γ chelate	α,γ chelate	$[\beta,\gamma]/[\alpha,\gamma]$
3.0	-8.30^b (20)	2.91 (22)	not detected	11.2^e		>20
	-20.74^c (20)	-10.06^c (22)		10.7^f		
3.51	-8.28^b (19)	3.25^b (19)	-0.60^h	11.5^e		
	-20.73^c (19)	-10.0^c (19)		10.7^f	7.7	15
4.40	-7.96^b (19)	3.35^b (22)	-0.59^h	11.3^e	$7.4^{e,g}$	
	-20.60^e (19)	-9.91^d (21,22)	-19.4^h	10.7^f	1.2^f	2.8
5.0	-7.90^b (20)	3.51^b (22)	-0.55^h	11.4^e	$7.4^{e,g}$	2.3
	-20.49^c (19)	-9.92^c (21)		10.6^f		
5.45	-7.58^b (20)	3.42^b (22)	-0.51^b (21)	10.9^e	$7.1^{e,g}$	
	−20.47 (20)	-9.87^d (22,21)	-19.44^e (21)	10.6^f	1.0^f	2.0
5.72	-7.35^b (21)	3.41^b (22)	−0.39 (22)	10.8	7.0	1.5
	−20.30 (21)	−9.73 (21,22)	−19.42 (22)	10.6	0.9	
7.7	-5.38^b (21)	3.07^b (21)	-0.34^b (22)	8.45^e	$5.0^{e,g}$	0.1
	-19.48^c (21)	-9.68^h		9.8^f		
8.41	-3.88^b (19.6)	3.13^h	-0.14^b (21.7)	7.0^e	$3.7^{e,g}$	<0.1
	-18.99^e (19.5)	-9.5^h	-19.99^c (22.1)	9.5^f	-1.0^f	
8.96	-3.56^b (20.2)		-0.22^b (21.7)		3.4	
	-18.21^c (20.1)		−19.47 (21.7)		0.74	<0.05

[a] Exact species depends on pH. [b] Doublet. [c] Triplet. [d] Doublets of doublet. [e] Coordination chemical shifts for γ-phosphorus atoms (negative and positive signs indicate upfield and downfield shifts). [f] Coordination chemical shifts for β-phosphorus atoms. [g] Coordination chemical shifts for α-phosphorus atoms. [h] Peaks appear as broad and no coupling was resolved.

limiting. The sequence of reactions for phosphate coordination to $PtCl(dien)^+$ can then be represented by eqs 9–11. For the

$$PtCl(dien)^+ + H_2O \xrightarrow{k_1} Pt(H_2O)(dien)^{2+} + Cl^- \quad (9)$$

$$PtCl(dien)^+ + P_x \xrightarrow{k_2} Pt(P_x)(dien) + Cl^- \quad (10)$$

$$Pt(H_2O)(dien)^{2+} + P_x \xrightarrow{fast} Pt(P_x)(dien) + H_2O \quad (11)$$

P_x = ortho-, pyro-, or triphosphate anions

reaction of $PtCl_2(en)$ with pyro- and triphosphate, we note that the final products are chelates and that no monodentate phosphato complexes were detected as intermediates. The formation of the monodentate complex can then be taken as the rate-limiting step, followed by rapid ring closure to yield the chelates according to reactions 12–15.

$$PtCl_2(en) + H_2O \xrightarrow{k_1} PtCl(H_2O)(en)^+ + Cl^- \quad (12)$$

$$PtCl_2(en) + P_x \xrightarrow{k_2} PtCl(P_x)(en) + Cl^- \quad (13)$$

$$PtCl(H_2O)(en) + P_x \xrightarrow{fast} PtCl(P_x)(en) + H_2O \quad (14)$$

$$PtCl(P_x)(en) \xrightarrow{fast} Pt(P_x)(en) + Cl^- \quad (15)$$

P_x = pyro- or triphosphate anions

The formation of triphosphate chelates is accomplished predominantly via the aquated complex, while a significant contribution by the direct reaction of $PtCl_2(en)$ should be recognized for the formation of pyrophosphato chelate. Earlier,[14] we noted that pyro- and triphosphato chelates were formed through the monodentate intermediate by using $PtCl_2(NH_3)_2$. The unimolecular rate constants for the formation of such intermediates ($k_1 + k_2[P_x]$) were comparable to those for the disappearance of intermediates ($k_1 + k_2[P_x]$) were comparable to those for the disappearance of intermediates to yield phosphato chelates. We do not observe significant departure from single exponential kinetic curves, and no intermediate can be detected during the time course of the reaction. We then estimate that the rate constants for ring closures must be at least 7 times that for formation of intermediates.[34] In the absence of any reacting nucleophile, the rate

Table VI. Rate Data for the Formation of Phosphato Complexes of Platinum(II)[a] at 40 °C, pH 6.0, and μ = 0.5 M ($NaClO_4$)

reaction[b]	$10^2[P_x]$, M	10^4k_0, s^{-1}	10^4k_1,[c] s^{-1}	k_2,[c] M^{-1} s^{-1}
$PtCl(dien)^+ + P_1$	1.0	8.9		
	3.0	14	6.2	2.7×10^{-2}
	4.0	17		
$PtCl(dien)^+ + P_2$	1.0	7.2		
	1.9	8.7	5.7	1.5×10^{-2}
	3.5	11		
$PtCl(dien)^+ + P_3$	1.0	8.5		
	3.0	11	7.4	1.2×10^{-2}
	4.0	12		
$PtCl_2(en) + P_2$	1.0	1.3		
	4.0	1.9	1.1	1.9×10^{-3}
	5.0	2.1		
$PtCl_2(en) + P_3$	1.0	1.2		
	4.0	1.3	1.1	4.6×10^{-4}
	5.0	1.4		

[a] Concentrations of $Pt(dien)Cl^+$ were in the range 5×10^{-4} M to 7×10^{-4} Mand those for $PtCl_2(en)$ were in the range 3×10^{-4} to 5×10^{-4} M. [b] P_1 through P_3 represent ortho-, pyro-, and triphosphate anions. [c] Rate constants obtained from the linear least-squares fit according to eq 8 utilizing k_0 values.

constant for the second aquation is smaller than that for the first. It appears then that monodentate phosphato complexes exert a labilizing effect on the second chloro ligand more in $PtCl_2(en)$ than in $PtCl_2(NH_3)_2$. Stronger trans influence by the phosphate ligands (as compared to water) may be due to chelate effect and to intramolecular hydrogen bonding (between the phosphate oxygen and amine hydrogen) of the monodentate phosphato complexes. We cannot say why such an effect is more pronounced in $PtCl_2(en)$ than in *cis*-$PtCl_2(NH_3)_2$.

III. Kinetics and Mechanisms of Isomerization of (Triphosphato)platinum(II) Chelates. On the basis of our NMR characterizations, we conclude that at pH 5.72, about 60% of triphosphate chelate is in the β,γ-isomeric form whereas at pH >7.7, 90% of the complex remains in the α,γ form. When the pH was raised from 5.7 to 8.3, ^{31}P peaks due to the β,γ complex almost completely disappear, and peaks for the α,γ chelate grow. Conversely, the dominant α,γ form at higher pH is converted to the β,γ form when the pH was lowered to 3.0. The estimated

(34) Kinetic profiles obeying consecutive first-order reaction sequences do not show appreciable deviations from linearity in first-order plots within the first 3 half-lives if the rate constants differ by more than a factor of 7. See, for example, ref 22.

half-lives for $\beta,\gamma \rightarrow \alpha,\gamma$ or $\alpha,\gamma \rightarrow \alpha,\gamma \rightarrow \beta,\gamma$ conversions did not depend on initial platinum concentration, indicating that this isomerization is a first-order process. Addition of 0.1 M Cl^- did not change the half-lives significantly, nor were we able to detect any other new phosphato products. The estimated first-order rate constants at 25 °C for $\alpha,\gamma \rightarrow \beta,\gamma$ (pH 3.5) and for $\beta,\gamma \rightarrow \alpha,\gamma$ (pH 7.7) were estimated as 2×10^{-3} s^{-1} and 3×10^{-3} s^{-1}.

The rapid isomerization reaction is largely intramolecular. With $[Cl^-] \gg [P_3O_{10}^{n-}]$, it is expected that Cl^- would compete with the triphosphate if the reaction were to proceed largely through a solvent-assisted pathway. Absence of monodentate phosphato complexes precludes any major contribution by this pathway. A mechanism consistent with our data is shown in Scheme I. (Charges are omitted.)

An attack by the unbound α-phosphate group leads to a trigonal-bipyramid transition state. A cleavage of the Pt–O bond of the coordinated α-phosphate should result in the α,γ complex (V). The attack is facilitated by the presence of a deprotonated phosphate group at higher pH. Furthermore, the unbound phosphate is uniquely positioned to form a hydrogen bond with the amine hydrogens. Such bond formation should bring the phosphate oxygen in close proximity to the platinum atom and lower the energy barrier for the isomerization. We note that the formation of the β,γ isomer predominates below pH 4, while the α,γ form is preferred above pH 6. We were unable to determine the acidity constants for these complexes owing to a small change in the chemical shifts and the absence of one or the other isomer in the lower and higher pH values. However, the pH-dependent chemical shift data do support two acidity constants near 10^{-4} and 10^{-6} for the β,γ complex and an acidity constant for the α,γ complex of 10^{-6}. These estimated acidity constants and the distribution of isomers as a function of pH support our mechanism of isomerization (Scheme I).[35]

The rate for isomerization is at least 10 times greater than that for formation of triphosphate chelates. It is therefore most likely that the β,γ chelate is formed initially and then rapidly isomerizes to the α,γ chelate.

Cornelius and Reibenspies[36] proposed that the linkage isomerization of $Co(H_2P_3O_{10})(NH_3)_4$ proceeds through dissociative pathways. Isomerization rate constants for cobalt(III) complexes are about 3 orders of magnitude smaller than for the platinum(II) complexes investigated here.

Acknowledgment. Support of this research through grants from the National Institutes of Health (GM 40006-02) and Kent State University Research Council is gratefully acknowledged. We thank Johnson Matthey Co. for the loan of K_2PtCl_4 and Professors E. S. Gould and J. Reedijk for valuable suggestions.

(35) Two points by a reviewer deserve response. The first pertains to the change in chemical shift (above pH 6) of the α,γ-phosphorus atoms if the α,γ-complex is deprotonated near neutral pH. This complex may not be fully deprotonated near neutral pH. Three acidity constants are expected for this complex, corresponding to the loss of one proton each from the α-, β-, and γ-phosphate groups. Higher acidity constants are expected for the coordinated phosphate group, as compared to the similar constant for the uncoordinated β-phosphate group. A small secondary change in the chemical shift of α- and γ-phosphorus atoms perhaps reflects the deprotonation at the uncoordinated middle phosphate group. A second point concerns the possibility of a rapid equilibrium between the α,γ complex and a monodentate complex near neutral pH values. This can be ruled out, on the basis of the observation that aquation of platinum(II) phosphophato chelates is extremely slow ($t_{1/2} \approx 10$ h at pH 7) and is shown to be acid-catalyzed (see ref 7b).

(36) Reibenspres, J. H.; Cornelius, R. D. *Inorg. Chem.* **1984**, *23*, 1563.

Contribution from the Dipartimento di Chimica Inorganica e Struttura Molecolare, Università di Messina, Salita Sperone 31, Vill. S. Agata, 98166 Messina, Italy

Kinetic Study of β-Hydride Elimination of Monoalkyl Complexes of Platinum(II): Effects of Varying the Alkyl Chain Length or the Cis Group in the Reaction of *cis*-Bis(triethylphosphine)(alkyl)(halo or pseudohalo)platinum(II) Complexes

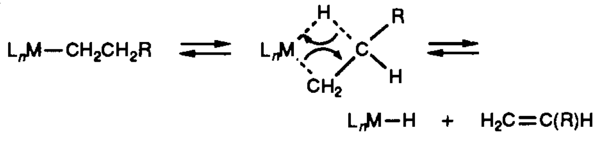
Giuseppe Alibrandi, Luigi Monsù Scolaro, Domenico Minniti,* and Raffaello Romeo*

Received September 14, 1989

The monoalkyl complexes *cis*-$[Pt(PEt_3)_2(R)Br]$ (R = C_2H_5, C_2D_5, n-C_3H_7, n-C_4H_9) and *cis*-$[Pt(PEt_3)_2(n\text{-}C_4H_9)X]$ (X = Cl, Br, I, NO_2, N_3, SCN, SeCN) undergo a facile β-hydride elimination in acetone, yielding *trans*-$[Pt(PEt_3)_2HX]$ and olefins. No alkanes are produced in these reactions that go to completion and are unaffected by the presence of an excess of halide ion in solution that serves to prevent a possible concurrent geometrical isomerization. The corresponding trans-monoalkyl species are stable under the same experimental conditions. The systems were characterized by ^1H and ^{31}P NMR. The rates of thermal decomposition were obtained by GLC, measuring the relative amounts of volatile products at various times. The ethyl complex decomposes at a rate ten times slower than that of the n-propyl and n-butyl analogues. For the complexes *cis*-$[Pt(PEt_3)_2(R)Br]$, the activation parameters are as follows: R = C_2H_5, $\Delta H^* = 101 \pm 2$ kJ mol^{-1}, $\Delta S^* = +5 \pm 4$ J K^{-1} mol^{-1}; R = n-C_3H_7, $\Delta H^* = 91 \pm 4$ kJ mol^{-1}, $\Delta S^* = -7 \pm 10$ J K^{-1} mol^{-1}; R = n-C_4H_9, $\Delta H^* = 90 \pm 2$ kJ mol^{-1}, $\Delta S^* = -4 \pm 4$ J K^{-1} mol^{-1}; R = C_2D_5, $\Delta H^* = 99 \pm 2$ kJ mol^{-1}, $\Delta S^* = -10 \pm 5$ J K^{-1} mol^{-1}. At 298.16 K, the kinetic isotope effect ($k_d(C_2H_5)/k_d(C_2D_5)$) is 3.1. The rates of decomposition of the complexes *cis*-$[Pt(PEt_3)_2(n\text{-}C_4H_9)X]$ are strongly dependent on the nature of the X group, the overall difference of reactivity being at least 4 orders of magnitude between the first and the last members of the series. The reactivity sequence X = N_3 < NO_2 < Cl < NCS < Br < NCSe < I correlates well with some NMR parameters ($\delta(^1H)$, $\delta(^{195}Pt)$, and $^1J(PtP)$) of the *trans*-$[Pt(PEt_3)_2HX]$ hydride products. The distribution of the olefin products, 1-butene, *cis*-2-butene, and *trans*-2-butene is also dependent on the nature of X. The most probable mechanism for the thermolysis involves fast and reversible β-hydride elimination and olefin insertion in a pre-rate-determining step, followed by slow olefin loss from a 5-coordinate $[PtL_2(H)(olefin)X]$ intermediate.

Introduction

The ease with which a hydrogen atom transfers from the β-carbon atom of an alkyl chain to the metal to produce a metal hydride as in the reaction



(1)

is of fundamental importance for the stability of organotransition-metal compounds.[1] Indeed, β-elimination is the best documented low-energy route leading to transition-metal–carbon

(1) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. C. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987; Chapter 6. Yamamoto, A. *Organotransition Metal Chemistry*; Wiley: New York, 1986; Chapter 6. Braterman, P. S.; Cross, R. J. *Chem. Soc. Rev.* **1973**, *2*, 271. Davidson, P. J.; Lappert, M. F.; Pearce, R. *Chem. Rev.* **1976**, *76*, 219. Schrock, R. R.; Parshall, G. W. *Chem. Rev.* **1976**, *76*, 243. Baird, M. C. *J. Organomet. Chem.* **1974**, *64*, 289.

0020-1669/90/1329-3467$02.50/0